Management of Complex Extremity Injuries

Tourniquets, Compartment Syndrome Detection, Fasciotomy, and Amputation Care

Robert M. Rush Jr, MD[a],[*], Edward D. Arrington, MD[b],
Joseph R. Hsu, MD[c]

KEYWORDS

- Extremity injury • Mangled extremity • Amputation • Compartment syndrome
- Fasciotomy • Prosthesis

KEY POINTS

- Save the patient first.
- Tourniquets save lives and limbs.
- Most patients with mangled limbs require resuscitation with blood products and operative intervention.
- Damage control options for extremity trauma include tourniquets, shunts, splints, external fixators, amputation, adequate initial débridement, and fasciotomy (both therapeutic and prophylactic). For mangled extremities, the initial procedure is rarely the last.
- Save the injured limb if possible—and reasonable—at first. If there is a question on whether or not limb salvage or amputation should be undertaken, get another surgeon's opinion.
- A reasonable conversation with the patient after limb salvage could include the following: "We saved your extremity for now, but it may or may not be as functional as a prosthetic limb. Time will tell. You (and your family) will be included in the decision to either continue with limb salvage or to opt for amputation."
- Regardless of your initial decision to amputate or salvage, a patient's preinjury socioeconomic status and personality greatly influence the patient's rehabilitation potential and ultimate functional result.
- Orthotic devices for dysfunctional, salvaged limbs are improving.

surgical.theclinics.com

Report Documentation Page		Form Approved OMB No. 0704-0188

1. REPORT DATE **01 AUG 2015**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Management of complex extremity injuries: tourniquets, compartment syndrome detection, fasciotomy, and amputation care**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Rush Jr. R. M., Arrington E. D., Hsu J. R.,**		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **United States Army Institute of Surgical Research, JBSA Fort Sam Houston, TX**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **UU**	18. NUMBER OF PAGES **21**	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**			

INTRODUCTION

When it comes to traumatic injuries, the extremities are the most exposed and most frequently affected body part. The arms and legs are exposed to a wide range of wounding mechanisms from falls to high-speed vehicular crashes and industrial accidents. Similarly, combat injures to the extremities result from blasts, multiple fragment munitions, and high-velocity weapons. The heavy toll of these injuries is especially apparent when caring for patients sustaining multiple proximal amputations or mangled limbs from the impact of an improvised explosive device. As the devastation of modern weaponry has increased over the past decade of war, so have the remarkable advances in the management of complex extremity trauma.

Complex extremity injuries, or mangled extremities, are those that have sustained a combination of bony, vascular, skin, and soft tissue and/or nerve injury in which amputation may be necessary. When embarking on salvaging a severely injured limb, not only does a patient's acute injury and hemodynamic status need to be taken into account but also the ability to provide a functional outcome needs to be considered.

Herein is a discussion of some of the highlights of recent advances in the treatment of complex extremity trauma (illustrated in **Fig. 1**).

Fig. 1. Complex extremity trauma and amputation care have advanced greatly over the past decade. The progression from (*A*) initial presentation to (*B*) initial débridement to (*C*) early rehabilitation and through (*From* Hermes LM. Military lower extremity amputee rehabilita tion. Phys Med Rehabil Clin N Am 2002;13:45 66; with permission.) (*D*) the process of recovery back to full function. (*Courtesy of* Reuters/Jason Reed; with permission.)

PREHOSPITAL CARE

Recent advances in the prehospital management of trauma patients are discussed in detail in the article by Kerby and colleagues elsewhere in this issue. For patients sustaining extremity trauma, the emphasis is on saving life over limb; priorities include

- Compressing sites of external bleeding
- Protecting patient airway via the simplest means possible
- Decompressing suspected tension pneumothraces
- Immobilizing fractures and potential spinal injuries
- Preventing hypothermia.

Patients are expeditiously transferred to an emergency department or first surgical capability as soon as possible.

Care at the point of injury as well as care en route and in emergency rooms includes the following and differs slightly depending on the environment and the number injured. First and foremost, ensure the safety of medical personnel—either by moving the patients to a safe location or by nullifying the danger—such as returning fire to suppress immediate enemy threats in a military setting. Once provider safety is established, direct pressure at the site of bleeding followed by a compressive dressing are the first and second maneuvers in the treatment of any bleeding wound. Given that the leading cause of preventable death from trauma is hemorrhage, if a patient has obvious external bleeding from the extremities that a simple tourniquet or hemostatic dressing could stop, then these maneuvers may be as important as establishing an airway. For traumatic amputations, a tourniquet should be applied to an intact portion of the extremity proximal to the injury.

Tourniquet Placement

Although any type of strap that can be wrapped around an extremity and held in place can work, tourniquets with a windlass are effective in stopping arterial bleeding when placed appropriately (Fig. 2). The most important factor in successfully placing a windlass tourniquet is to ensure that the strap/belt portion is fitted as tightly as possible around a casualty's injured extremity before tightening the windlass. With most windlass tourniquets, the amount of tightening, once appropriately strapped onto a limb, is 3 cm of linear length (not radial distance). Some investigators advocate field

Fig. 2. Lower extremity injury requiring the use of 2 Combat Application Tourniquets.

pneumatic tourniquets (similar to a large blood pressure cuff) that are reported to apply more effective pressure over a wider area, although field-testing in combat has not been reported.[1] The Israeli Defense Forces use a simple elastic band as a tourniquet (described in the article by Soffer elsewhere in this issue). Regardless of the tourniquet type, reassessment is essential, especially as patients are resuscitated—as intravascular volume is restored and blood pressure increases, the more likely an initial tourniquet is to fail if not retightened. All large military series have shown a survival benefit from the early use of tourniquets for complex extremity injuries and there have been no permanent adverse effects of tourniquet application in several large series reported from the battlefield, including no tourniquet-caused amputations.[2–6]

Pitfalls

The application and maintenance of a tourniquet is not always easy. Recognizing when to apply a tourniquet requires training. During the course of patient transport or resuscitation, reapplication or the placement of additional tourniquets proximally may be required. The time and circumstances of tourniquet application must be communicated to the transport team and to the receiving facility. Tourniquets must be placed as distally as possible to stop the bleeding but limit ischemic tissue and nerve compression. Frequent re-evaluation to ensure there is no pooling of blood under sheets, equipment bags, or drapes is mandatory. Limb cooling may have an added protective effect if the tourniquet time is prolonged greater than 4 to 6 hours, although this technique is best performed with other systemic warming measures in place because hypothermia kills patients more quickly than a prolonged tourniquet.[7] Recent preclinical evidence suggests that the duration of ischemia should be limited as much as possible, especially in the setting of shock.[8,9] Practically speaking, tourniquets should be removed as soon as surgical control of the hemorrhage can be obtained.

Hemostatic Dressings

One of the most controversial developments over the past decade of war is the multitude of hemostatic dressings available to augment hemorrhage control. The US Army now fields Combat Gauze (Z-Medica Corporation, Wallingford, CT, USA), a kaolin-impregnated gauze that activates the natural clotting cascade by activating factor XII and initiates platelet adhesion. Some studies have found this hemostatic dressing effectively controls hemorrhage not amenable to tourniquet application.[10–12] Most common sites for use are in the groin and axilla, though any of these dressings can be used to augment hemorrhage control provided by tourniquets as well as potentially decreasing tourniquet time.[13]

Splints

Temporary skeletal fixation is important to minimize further bleeding; minimize further injury to exposed and unexposed nerves, soft tissue, and vessels; and reduce pain. Splints can be applied over tourniquets as long as both the tourniquet and bleeding portions of the open wound remain accessible and visible. The principles of splinting are to immobilize the joints above and below the fracture/injury site. If the extremity is mangled and thus fractured in many places, extend the splint to fit the entire extremity.

Other Considerations at Point of Injury

Gather amputated parts and transport with patients because this tissue can sometimes be used as spare parts for reimplantation or bone graft. Administer an antibiotic and/or tetanus if transport time to an emergency room or first surgical capability is

delayed. Make sure all this is communicated in the handoff. Field débridement of wounds is not advocated except in extreme circumstances (eg, patient extraction can only be accomplished by amputating the limb).

SCORING SYSTEMS: AMPUTATE OR SALVAGE?

Although many have been proposed, no scoring system is definitive in making the decision for limb salvage versus amputation in managing patients with complex extremity trauma. All the studies done in this area rely on applying well thought-out descriptions of extremity system derangements but are applied to a cohort retrospectively or in a prospective observational method—none are by prospective randomization of patients to amputation versus salvage groups.[14–20] Each does provide perspective and a framework in which to address these complex management problems. None of the scoring systems, however, reliably guides management when evaluated on other retrospective cohorts.[21–23]

Bosse and colleagues[24] published a large prospective study of severely injured lower extremities, the Lower Extremity Assessment Project (LEAP). This study of 601 patients was conducted at 8 level 1 trauma centers and eventually included 556 limbs in 539 patients with severe extremity injuries. The objective of this study was to prospectively evaluate 5 limb salvage scoring systems. Gustilo classification was recorded as well as treatment (salvage, immediate amputation, or delayed amputation). The treating surgeon was also asked to record the critical components of the Mangled Extremity Severity Score (MESS); the Limb Salvage Index; the Predictive Salvage Index; the Nerve Injury, Ischemia, Soft-Tissue Injury, Skeletal Injury, Shock, and Age of Patient score; and the Hannover Fracture Scale-97 during the study period. All these scoring systems were compared with treatment for sensitivities and specificities of predicting the need for amputation. The investigators determined that a low score was predictive of limb salvage whereas a high score did not necessarily predict the need for amputation. The investigators cautioned against the use of these scoring systems in clinical decision making when considering primary amputation.[14] The same group published an article that concluded that 2-year functional outcomes were in between limb salvage patients and amputation patients for lower extremity injuries and questioned the usefulness of heroic limb salvage efforts.[24]

Most validating studies for these scoring systems took place at level 1 trauma centers with specialists, resources, and multidisciplinary teams. Thus, the applicability of these data to smaller centers and military and rural settings, where misguided limb salvage could have fatal consequences, should be considered. The decision to amputate a severely injured extremity remains a difficult one that no single scoring system performed at the bedside or in the operating room is likely to simplify. It makes intuitive sense that a surgeon is not likely to calculate a complex score during an operation. By being aware of these systems and what predicts salvage, however, these scoring systems have given surgeons a thought process to aid in this difficult decision. These reports have also provided a common language with which new results may be reported and compared.

In another study performed by the Lower Extremity Assessment Project (LEAP) Study Group, looking at factors that led to decisions to amputate or salvage,[25] the most important factors considered were (1) muscle injury (as this relates to ultimate function), (2) absence of sensation (although this is controversial), and (3) injury to deep veins and arteries (especially the popliteal artery). This is how expert orthopedic and trauma surgeons thought through their decisions as prospectively recorded, thus outlining their priorities and their results. As medicine and techniques advance,

surgeons still have to rely on good judgment and on allocation of resources at the facility to abide by the old dictum, life over limb—not only limb but also an expedient recovery to a functional limb.

Decision to Amputate

Complex extremity trauma, also referred to as a mangled extremity, applies to those severely injured arms or legs where primary amputation may be considered a treatment option. There are no studies that have prospectively evaluated the factors that are involved in a decision to amputate or salvage a mangled limb. Ultimately, the decision for limb salvage or primary amputation must be made by the treating surgeon although input from additional colleagues or specialists is encouraged.

Base the decision on the known information. An adequate evaluation of the injury needs to be done depending on patient condition. If a patient is unstable, the evaluation needs to be done in the operating room where vascular control can be obtained and other life-threatening hemorrhage or injuries can be simultaneously addressed so that there is a live patient. If stable, a more thorough vascular and neurologic assessment can be completed after initial skeletal alignment in an emergency department.[26] The questions to ask are

1. Is limb salvage feasible (considering the damaged extremity systems)?
2. Is limb salvage advisable (given patients hemodynamic status)?
3. If embarking on salvage, what are the management priorities?
4. When should secondary amputation be considered?

If possible, include the patient and patient's family in the decision early (sometimes not possible). Scalea and colleagues and the Western Trauma Association[26] have provided an excellent and up-to-date algorithm to help with the management of immediate postinjury mangled extremities that are sustained in civilian trauma settings (**Box 1**). In military populations where high-energy ballistic injuries are prevalent, civilian scoring systems do not necessarily apply. Brown and colleagues[27] found that the ischemia and generally poor condition of the patients sustaining high-energy combat wounds led to a greater need for primary amputation. Conversely, a MESS score greater than or equal to 7 did not mandate amputation. The LEAP study goes a bit further and is helpful in that the degree of soft tissue injury as it relates to best-guess functional outcome is important, ensuring that factors, such as a patient's means (ie, economic and social) to perform rehabilitation and multiple limb reconstructive procedures, is present.

Sometimes secondary amputation is desired and should not be considered a failure. This has become evident as results from the military LEAP study are released, where it was found that most soldiers undergoing amputation attained a better level of postinjury function more quickly than those undergoing complex extremity salvage (James Ficke, COL, personal communication, 2012).

INITIAL EVALUATION AND MANAGEMENT

Most patients sustaining complex extremity trauma require resuscitation with blood products and operative intervention. Patients with a mangled extremity are at some risk for both early and late death from one of several mechanisms:

- Unrecognized or ongoing hemorrhage from the limb
- Hemorrhage from other injuries
- Wound sepsis from inadequate débridement or necrotizing soft tissue infections

---

Box 1
Predictors of amputation in complex extremity trauma

Systemic factors

Age >50 y

High energy transfer

Persistent hypotension (<90 mm Hg)

Bony skeletal factors

Gustilo type III A with significant tissue loss or nerve injury, associated with fibular fracture and displacement of >50% and comminuted segmental fracture or high probability of need for bone graft

Gustilo type III B and type III C tibial fractures

Gustilo type III open fractures of the pilon

Gustilo type III B open fractures of the ankle

Severe open injury to the hindfoot or midfoot

Soft tissue factors

Large, circumferential tissue loss

Extensive closed soft tissue loss or necrosis

Compartment syndrome with myonecrosis

Neurologic factors

Confirmed nerve disruption, in particular, the tibial nerve

Vascular factors

Prolonged warm ischemia time, >6 h

Degree of vascular segment loss

Proximal vascular injury (femoral greater risk than popliteal or more distal)

Absence of viable distal anastomotic target

Data from Scalea TM, Dubose J, Moore EE, et al. Western Trauma Association critical decisions in trauma: management of the mangled extremity. J Trauma 2012;72(1):86 93.

- Unrecognized massive ischemia leading to renal and multiorgan failure
- Thromboembolic events.

Patients with traumatic amputations die from the same causes.

Priorities

As with prehospital care, the management priorities in these patients emphasize saving life over limb. These priorities include

1. A live patient—what needs to be done immediately to ensure this:
   a. Stop the bleeding.
   b. Establish/maintain an airway.
   c. Ensure respiration/breathing.
   d. Damage control resuscitation—the order of these steps depends on a patient's stability and individual injury pattern but ideally should be addressed in a multiteam or simultaneous approach.

2. Do no more harm to the live patient:
    a. Limit further disability (head and spine trauma).
    b. Control contamination/infection (tetanus and initial antibiotics).
    c. Prevent hypothermia.
3. Operative management (highly dependent on local resources):
    a. Damage control principals—do as much or as little as possible at each operative intervention or point of care to ensure that the patient stays alive.
    b. Ensure hemostatic resuscitation continues (blood/platelets/plasma).
    c. Replace field tourniquets with pneumatic tourniquets while assessing injuries.
    d. Give tetanus prophylaxis and appropriate antibiotics depending on the degree of contamination of the wounds. Do not forget to redose if necessary.
    e. Decide on an order between skeletal fixation and revascualization procedures knowing that shunting of vascular injuries and external fixation are excellent damage control techniques that should not require a lot of time to perform. Shunts have been used successfully to keep an extremity perfused over prolonged periods of time as well as over great evacuation distances and have proved a key advancement over the past 10 years of war.[28–32] Although nothing is better than autologous vein graft from an unaffected limb, there may not be time to perform bypass grafting in many settings involving complex extremity trauma because most of these patients have sustained polytrauma. If the major artery and vein of an extremity are both damaged, attempt to shunt or repair both as long as the patient can tolerate the length of the procedure. Otherwise, at least establish inflow if limb salvage is to be undertaken.
    f. Ensure adequate débridement of all devitalized soft tissue (no irrigation under high pressure because this may extend contamination into clean tissue plains).
    g. Consider primary and/or prophylactic fasciotomy of damaged and distal compartments
    h. Maintain as much nerve length as possible and mark nerve ends if patient hemodynamic status permits. These nerves can be used to restore some muscle innervation, which may prevent atrophy and improve limb or prosthetic function.
    i. Use wound vacuum-assisted closure (VAC) devices liberally once the wound bed is clean. For massively contaminated, high-energy open wounds, a vacuum dressing may need to be deferred for one or several operations.
4. Multiteam approach:
    a. Triage and timing of care is critical in the management plan. The trauma surgeon coordinating a patient's care is the team leader and negotiates with consultants as to the timing and complexity of procedures, simultaneous procedures, and length of anesthesia as well as allowable blood loss.
    b. For cases of single limb injuries and in multitrauma patients, several teams are necessary—one for each major body cavity and limb. Each limb may have multiple teams involved in the injury management (eg, vascular, orthopedics, and plastics).
    c. Team priorities must be made by the trauma surgeon in charge regardless of that surgeon's primary surgical discipline.

COMPARTMENT SYNDROME AND FASCIOTOMY

In at-risk extremities, compartment syndrome must be anticipated, investigated, and treated. Fascial compartments swell and become tight when they are ischemic for a prolonged period of time (usually >4–6 hours) and then reperfused or when the extremity is directly injured by impact or energy transfer. In a mangled extremity, both mechanisms are at play. After such an insult, tissue within the fixed fascial

envelopes of the extremity begins to swell, and, as this process continues, intracompartmental pressure rises until venous obstruction occurs.

Once the low intramuscular arteriolar pressure is exceeded, blood is shunted away from end muscular capillary beds. This reduced flow generally occurs at compartment pressures of 3 mm Hg to 40 mm Hg or greater for longer than 8 to12 hours. Arterial inflow continues at first, increasing tissue edema, leading to what Mubarak and Owen[33] define as compartment syndrome, an elevation of the interstitial pressure in a closed osseofascial compartment that results in microvascular compromise. Arterial inflow can continue despite the presence of compartment syndrome and the loss of a distal pulse is thus a late finding.

Nerve tissue is affected first by the subsequent end-tissue hypoxia causing pain on passive motion seen early in the development of compartment syndrome, sparing distal pulses until late in the course. Damage to muscle can occur even with normal flow into a compartment when pressures reach 30 mm Hg to 40 mm Hg for 8 hours. Studies have shown that pressures of 40 mm Hg sustained for 14 hours did not cause nerve dysfunction. Higher compartment pressure, however, take less time to cause permanent functional loss of nerve and muscle function.[34] Reperfusion of the extremity after vascular repair can cause massive swelling of some of the compartments, resulting in a secondary compartment syndrome, even after short-term disruption of blood flow (2–6 h). This can place a potentially viable limb at risk for amputation if compartment syndrome is missed.[35,36]

Detection

The diagnosis of compartment syndrome can be challenging. Missing this injury is usually devastating and can result in a Volkmann contracture or ischemic contracture of the compartment musculature, compounding the severity of the original injury and further compromising limb salvage and eventual function. Compartments with non-compliant surrounding structures or tissue are generally more at risk, especially the anterior and deep compartments of the lower leg and the volar compartment of the forearm. Anatomy of the compartments of the lower leg and forearm is shown in **Fig. 3**. Other compartments that are susceptible to increased pressures are in the hands and feet, thigh, and gluteal fascial envelopes.
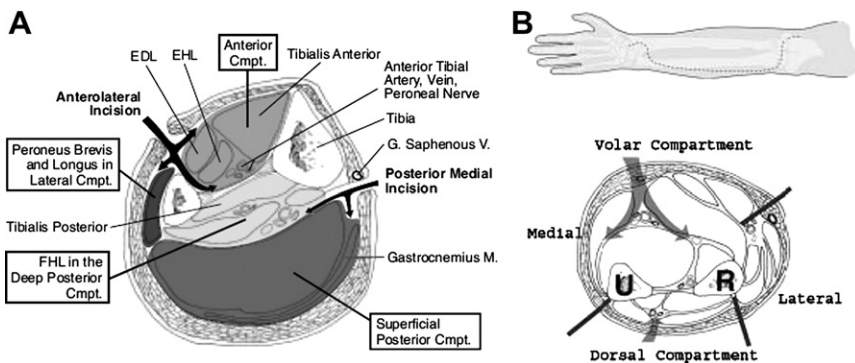
Fig. 3. (*A*) Lower extremity cross section at the midcalf depicting locations of 4 compartments requiring fasciotomy for the treatment or prevention of compartment syndrome. (*B*) Forearm cross section showing compartments requiring fasciotomy for upper extremity compartment syndrome. Also shown is the required incision for fasciotomy of the forearm needed for release of volar compartments (*B*). Cmpt, compartment; EDL, extensor digitorum longus; EHL, extensor hallucis longus; FHL, flexor hallucis longus; G, greater; M, muscle; R, radius; U, ulna; V, vein.

Injuries to the extremities, such as fractures, massive soft tissue trauma (by blunt and penetrating high energy mechanisms), intracompartmental bleeding, arterial or venous injury, limb compression, and burns (especially circumferential and electrical), warrant a heightened index of suspicion.[37] In awake patients, a tight compartment associated with the appropriate mechanism of injury may lead to suspicion of the diagnosis. Pain out of proportion to the injury at that level on passive motion—as the compromised muscle slides through the affected compartment—is the most common early finding. Paresthesias and numbness can be early signs. The loss of 2-point discrimination is a sensitive sign in differentiating compartment syndrome from raised intracompartmental pressure alone.[38] In dealing with the mangled extremity, however, most patients have sustained multisystem trauma (especially those sustaining concomitant head injuries) that may preclude a reliable examination, are frequently taken back to the operating room for damage control and subsequent procedures, and remain sedated. In these patients, intracompartmental pressures should be measured.

There are several methods for measuring intracompartmental pressures. Most involve needles and/or catheters. Using the Stryker compartment measuring device is an easy way to do this (Fig. 4).[39] McQueen and Court-Brown[40] used a pressure differential of less than 20 mm Hg between the compartment measurement and diastolic pressure (or <30–40 mm Hg from mean arterial pressure) to determine the need for fasciotomy. At a pressure differential equal to or greater than 20 mm Hg, as opposed to absolute compartment pressures, no compartment syndromes were missed and no unnecessary fasciotomies were performed in tibial diaphyseal fracture patients in this study.

Recently, near-infrared spectroscopy, a continuous but noninvasive method for detecting compartment syndrome, has been shown to have a higher positive predictive value of detecting truly increased compartment pressures than measuring compartment pressures via needles or catheters.[41,42] Near-infrared spectroscopy transmits light that passes through skin and subcutaneous tissue but is reflected or absorbed by hemoglobin, depending on the oxygenation-reduction state of the molecule. This can be related to the ischemic state of muscle as in compartment syndrome. The measurements seem to be accurate even in states of circulatory shock.[43]

Fig. 4. Portable near infrared spectrometer for noninvasive diagnosis of decreased tissue blood flow. (*From* Vorwerk C, Coats TJ. The prognostic value of tissue oxygen saturation in emergency department patients with severe sepsis or septic shock. Emerg Med J 2011 Sep 21. [Epub ahead of print]; with permission.)

Regardless of the initial state of the compartment, a prophylactic fasciotomy is sometimes warranted. This is especially applicable to military settings, in cases of delayed transports in rural settings, and in managing mass casualties from disasters. In such circumstances, if a patient is currently at risk for a compartment syndrome or could develop a compartment syndrome, prophylactic fasciotomy should be strongly considered. Long-term complications of an inappropriate fasciotomy can lead to severe venous congestion, infections, scarring, and decreased range of motion of the joints above and below the fasciotomy in some cases. These risks must be weighed when contemplating the use of prophylactic fasciotomy.

Treatment

The treatment of compartment syndrome consists of fasciotomy, completion fasciotomy, and sometimes the judicial use of prophylactic or preventive fasciotomy. Ensure that previously applied casts, splints, and dressings are removed first. For the lower leg, 2 longitudinal incisions must be made, an anterolateral incision to decompress the anterior and lateral compartments and a posteromedial incision aimed at the posterior superficial and deep compartments (**Fig. 5**). Pitfalls include incomplete fasciotomy, where incisions in the fascia are not extended to the compartment limits both distally and proximally, thus not completely relieving the swelling and tightness along the length of the compartment. It is important to ensure that the length of the

Fig. 5. Double incision (medial and lateral) through which a complete 4 compartment fasciotomy of lower leg has been performed.

incision is long enough because there are reports in which the skin continued to cause compression after fasciotomy performed through short incisions.[44] A caveat to this is that compartment syndrome can still exist in open wounds and fractures and may require fasciotomies despite being open. Peripheral motor and sensory nerves must be avoided in the fascial incisions, especially the deep posterior compartment of the lower leg, where the posterior tibial neurovascular bundle runs just deep to the investing fascia.[45]

Fasciotomy Wound Management

Skin tension should be applied when there is skin available to minimize the need for skin grafts. Sterile dressings should be applied and changed frequently or a wound VAC device applied. On the resolution of underlying compartmental muscle swelling, the fascia and skin can be reapproximated in many cases. Finally, splint the extremity in the position of function after compartment releases. When closing the fasciotomy sites, close the medial wound first at expense of the lateral wound.

Crush/Ischemia/Reperfusion Injury and Rhabdomyolysis

Extremity trauma resulting from crush injures and ischemia-reperfusion injuries may result in rhabdomyolysis, hyperkalemia, or both. In these cases, myoglobin from the damaged tissue can be released with the potential of causing renal failure. For the detection of rhabomyolysis, marked elevation of tissue creatinine kinase of greater than 10,000 IU/L is suggestive. If there is no laboratory, "crankcase" or dark urine should lead to a high index of suspicion. Potassium can also be released, causing hyperkalemia and the potential of cardiac arrhythmias.

Treatment of rhabdomyolysis and of hyperkalemia is similar:

- Check for tourniquets and remove if possible.
- Restore intravascular volume.
- Alkalinize urine with sodium bicarbonate infusion.
- Infuse insulin, glucose, furosemide, and calcium.
- Ensure fasciotomies are complete and that any dead tissue is fully débrided.

If these measures prove unsuccessful, patients may require urgent dialysis if this therapy is available.

AMPUTATIONS

One of the most difficult decisions is when to amputate a mangled extremity. If a patient is delivered in extremis from multiple injuries that include a mangled extremity, an emergent or completion amputation can be life saving, even if limb salvage may have been an option in a more stable patient. When amputation is decided, avoid guillotine (straight perpendicular cut across the axis of the extremity) amputations because viable soft tissue may be lost—better to save all viable soft tissue, including skin, muscle, fascia, and nerves. This requires débridement and irrigation. Irrigation should be copious but not under pressure because this has shown to cause microscopic debris and bacteria to lodge in good tissue. If performing an amputation in a damage control setting or if there is contamination, do not close the skin. Also ensure that the bone is left as long as possible (as long as it is viable and has periosteal covering) so that it can act as a tension-producing splint for the soft tissue envelope. The bone can be cut back at the time of a more definitive repair.

When an amputation is decided on for the treatment of a severely injured extremity, there are several universal principles that should be considered:

1. Ensure that the level of the amputation is as low as possible while débriding all devitalized tissue. Avoid guillotine amputations because these remove elements of the soft tissue envelope surrounding the cut bone.
2. Salvage any viable flaps possible because the soft tissue is more important than the bone in the amputation. The posterior flap is the most important part of the soft tissue coverage of the bone for a below-the-knee amputation.
3. The definitive amputation procedure and stump closure do not have to be done at the time of the primary or at the time of secondary amputation procedure or washout.
4. In a contaminated wound, serial débridements may be required before final stump closure. Use wound VAC devices for open stumps and other open wounds usually after second débridement, because the time between first and second operations is usually between 12 and 24 hours, which sometimes nullifies the effectiveness of this form of dressing.
5. Keep tension on the remaining skin flaps directed distally.
6. Ask patients if they have seen or know the extent of damage to their extremity and include them and their families in on the decision-making process, if feasible. They should always be informed that amputation could be considered at any time during the course of reconstruction and rehabilitation.

The specific technique in performing an amputation is as follows[46]:

- Surgically prepare the entire limb, because planes of injury may be higher than they appear on the surface.
- Place a pneumatic tourniquet, if available; otherwise, use a prehospital tourniquet and prep it into the surgical field.
- Excise nonviable tissue: (1) debride necrotic skin and subcutaneous tissue, (2) remove devascularized, noncontracting muscle, (3) sharply debride tendons back to the level of viable muscle, and (4) excise grossly contaminated bone devoid of soft tissue that cannot be covered.
- Identify and ligate major vascular structures, including veins.
- Identify and gently pull nerves distally while cutting or ligating proximally to allow them to retract to a covered area for definitive amputations of the lower extremity. Upper extremity and proximal lower extremity nerves should be preserved in length, because these nerves can be used for innervation in reconstructive procedures using muscle flaps and advanced prosthetics. Large nerves should always be ligated.
- Place preserved muscle and skin flaps on gentle tension to avoid retraction, thus preserving maximal stump length.
- Do not initially close grossly contaminated stumps completely (**Fig. 6**).

Level of Amputation

The different levels of amputation are as many as the number of limbs needing to be amputated. A common misconception is that amputating through joints is not indicated when, in actuality, a knee disarticulation, for example, is much more functional than an above-the-knee amputation. Leaving the distal femur allows patients better balance when sitting and prosthetics for through-knee amputations are improving. If any of the tibia or surrounding tissue can be spared in a damage control setting,

Fig. 6. Aftermath of second débridement of a grossly contaminated stump wound on an amputated lower extremity with a wound VAC device applied.

however, save it because this allows for better skin and muscle tension for definitive repair. For ray amputations of the foot, removing the big toe in most cases is worse than a transmetatarsal amputation due to lack of balance in gait with the absence of the main digit. In the upper extremity, retention of limb length is more important than for lower extremity amputations, due to the difficulty in moving several prosthetic joints simultaneously (elbow and wrist). Moving two joints simultaneously is not possible and must be done sequentially leading to cumbersome and awkward movements, especially in transhumeral amputees. Furthermore, forearm amputations should attempt to retain at least half the radius for maximal function. Another important point for the mangled upper extremity is that even a very dysfunctional limb is better than an amputation as long as infection is avoided in the initial wound.

Complications

Complications exist in patients with amputated extremities and are a major reason the amputation group was found to have an almost equal degree of functional problems postinjury in the LEAP study as compared to the limb salvage group. Stump skin ulcers or blisters affect most patients occasionally, sometimes leading to wound breakdown with or without cellulitis. Chronic osteomyolitis can develop from the start or develop over time if a stump is not cared for properly. Psychologically, patients must go through a period of psychosocial adaptation and part of this process is mourning the loss of the extremity. Those with better support systems are able to shorten this process significantly and are more likely to return to better function than those without—similar to the functional outcomes in salvaged extremities. Although every patient has a sensation that the limb is still present, phantom limb pain, characterized by searing, burning, and throbbing pain in the "amputated" limb, occurs infrequently. Nerve blocks and other chronic pain medications usually control these symptoms. Mirror therapy has also been described as a useful therapeutic tool.[47] Revisional surgery is sometimes required for deep infections and bony protrusions of the skin. Dermatologic complications develop and mild forms of rashes are treated with lanolin or hydrocortisone cream. Low-grade skin infections and carbuncles can be treated with oral tetracycline.

Verrucous hyperplasia, or chronic venous congestion of the distal limb, occurs from lack of total contact with the prosthesis and requires refitting.

Heterotopic ossification (HO), the aberrant formation of mature, lamellar bone in nonosseous tissue, has emerged as a common complication of both amputated and salvaged mangled extremities over the past decade of war.[48–50] The increased prevalence of high-energy blast injuries is thought to be a major cause due to the marked activation or presence of osteogenic connective tissue progenitor cells found in these wounds.[51] In civilian trauma, complex lower extremity injuries in conjunction with traumatic brain injury and an elevated injury severity score are most commonly associated with later development of HO. Although operative excision remains the treatment of choice for symptomatic HO, preventive measures for high-risk limbs are being developed so that prophylactic treatment can begin closer to the time of injury. Radiation therapy given within 48 hours postoperatively or the administration of nonsteroidal anti-inflammatory drugs is shown to minimize the development of HO. Neither has been a viable option in the combat setting to this point but further risk stratification and diagnostic techniques may be able to identify patients most likely to develop HO after high-energy, combat-related wounds to further direct prophylactic treatment.[52]

PROSTHETICS AND REHABILITATION

Postinjury rehabilitation is vital for patients suffering severe extremity trauma whether the limb was salvaged or required amputation. Depending on the complexity of the extremity injury, rehabilitation of a salvaged mangled extremity can be more difficult than rehabilitation after a primary or secondary amputation. Rehabilitation often is accompanied by further reconstructive work, such as

- Limb-lengthening procedures, sometimes using the Ilizarov external external skeletal fixation device, as well as new frontiers in regenerative medicine (cortical bone scaffolding, muscle stem cell replantation, and nerve cell growth)
- Rotational skin flaps
- Myocutaneous transposition flaps (keep original vascular pedicle intact)
- Microvascular free flaps (complete autotransplantation of muscle or myocutaneous tissue group)
- Flaps or grafts from "spare parts"—using portions of a patient's own amputated limbs in reconstructing other injured extremities.

Lower limb and upper limb orthotics and prosthetics have undergone revolutionary improvements over the past decade mainly due to the United States' emphasis on helping military amputees return to and lead a productive life. There are many designs available for upper extremity and lower extremity prostheses, but, for the most part, the more proximal the amputation the more complex the prosthesis needs to be—because there are more joints to be mimicked and the more degrees of freedom needed.

New developments in lower extremity orthotics have been found to allow better functioning of salvaged extremities. Reasons for this are multifactorial and include the access to and development of supporting programs available to train with the new devices. Design of lower extremity orthotics must include the ability to maintain stability, relieve neurogenic pain, and allow for strength across a fused joint.[53] Several orthotics are available, including the Intrepid Dynamic Exokseletal Orthosis (IDEO) (Fig. 7). When using this energy-storing ankle-foot orthosis device for soldiers with salvaged lower extremities from combat injuries, the Center for the Intrepid in San Antonio, Texas, was able to return all the patients back to some form of athletic
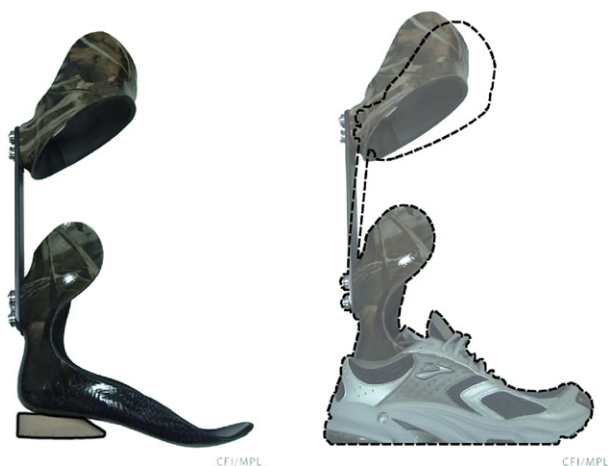
Fig. 7. The IDEO. (*From* Owens JG, Blair JA, Patzkowski JC, et al. Return to running and sports participation after limb salvage. J Trauma 2011;71(Suppl 1):S120 4; with permission.)

training and 8 patients to full running.[53] The orthosis alone was not the key component but the entire sequential rehabilitative sequence, including gait and exercise training, was essential for success. This is a major point brought out by the studies done by the LEAP group—that patients' pre-existing socioeconomic status and postinjury access to programs/equipment are key for them to becoming productive members of society after complex limb trauma.

Secondary or late amputation is a viable alternative for patients due to the rapid development of functional lower limb prosthetics as well as the rehabilitation resources dedicated to teaching patients, especially military amputees, how to use the new appendage. The recent Military Extremity Trauma Amputation/Limb Salvage (METALS) analysis of injured American warriors who sustained complex extremity trauma, including amputations, shows that both unilateral and bilateral lower extremity amputees scored better on the Short Musculoskeletal Functional Assessment index than did those who underwent limb salvage and the multiple, numbers of reoperations and courses of rehabilitation. Although there was no significant difference in return to work/active duty, depression, and chronic pain between amputation and limb salvage, amputees reported as engaging in more vigorous sports were less likely to have post-traumatic stress.[54] Another important note in this study is that 20% of the amputees underwent secondary amputation more than 1 month from original injury. The Center for the Intrepid at both the Walter Reed National Military Medical Center and at Brooke Army Medical Center focuses on this care and provide all returning amputees a near ideal environment for treatment and rehabilitation.

The arm is more complicated in duplicating than any type of lower extremity segment. Because of this, upper extremity limb salvage attempts should be more rigorous than lower extremity limb salvage. A dysfunctional upper limb can allow for stabilization of gait and apposition. Arm prosthetics have evolved from cosmetic or 1-D functional devices to myointegrated advanced limbs that look like and have nearly as many degrees of freedom as a real limb (eg, the DEKA [or Luke] arm designed by Kamen [Fig. 8]). Control of this arm can be done with a footplate device in the shoe and/or by connected residual nerves to pectoral muscles that can interface with electrodes on a breastplate. Although the human arm has 22° of freedom, the DEKA arm has 18°. As with orthotics for salvaged limbs, the rehabilitation and continued training
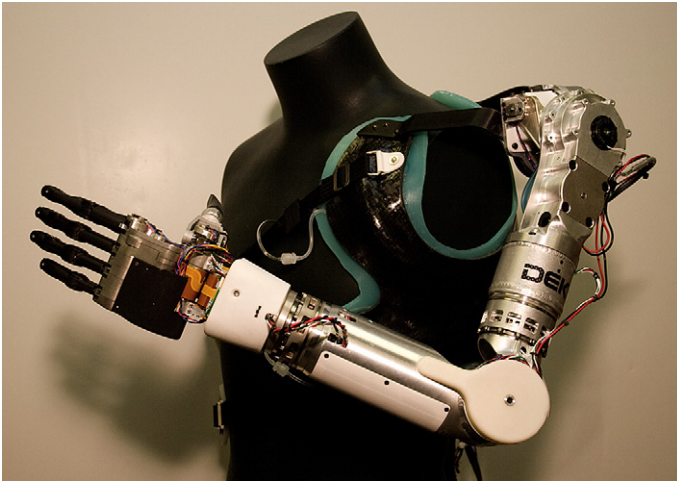
Fig. 8. DEKA arm with straps.

needed for these and other amputations to attain optimal postinjury function is essential and requires a systematic and multidisciplinary approach, including surgeon, physiatrist, physical therapist, psychologist, prosthetist, and patient's family.[55] Additionally, the Defense Advanced Research Projects Agency has funded research in cortical neural control prosthetics whereby electrode sensors/transducers are implanted on the surface of the cortex of the brain, and, through rigorous training, patients are able to control the prosthetic by actual thinking instead of having to perform some physical motion or muscle stimulation (such as the pectoralis implantation). Work by Ling and associates is on the forefront of limb replacement options.[56,57]

Although upper extremity replantation and transplantation is extremely technical, research in arm transplantation is evolving. There are case reports of several successful hand and arm transplants that have resulted in partial function. Common complications are rejection and lack of complete function.[58–61] Arm and hand replantation requires a clean-cut injury and is inappropriate for blast, crush, and high-energy mechanism injuries.

Lower limb prosthetics are somewhat simpler because there are fewer degrees of freedom to replace. The same technology is available for nerve implantation to control prosthetic ankle joints and knee joints. As with energy-transferring orthotics, lower extremity amputees can attain good function with energy transfer prosthesis. In general, the higher the amputation, the more energy that is required by patient to ambulate with a prosthesis. One of the key factors in prosthetics of the lower extremity is the socket fit of the stump—because this is where the most energy transfer occurs and where the new weight-bearing surface is located. Typically, regardless of the prosthetic, patients undergo multiple adjustments of their prosthetic in the socket area over a lifetime and may require stump revision as well.[62]

SUMMARY

Extremity injuries are common and can present a significant injury burden for patients, especially if an extremity is mangled. Those injuries requiring the need for a surgeon to decide on amputation versus limb salvage are less common except in the deployed military population, where this is a daily occurrence. For a bleeding, mangled limb, or traumatic amputation, a correctly applied tourniquet saves lives and limbs.

Following the treatment algorithms developed in civilian and military arenas over the past decade reduces morbidity and mortality in patients sustaining these injuries regardless of amputation or limb salvage. The decision to amputate or salvage a mangled limb can be difficult but if patients' hemodynamic status at presentation and what function they are likely to attain are taken into account, it can be easier. Secondary or delayed amputation is becoming a more viable option as prosthetics continue to improve at remarkable rates. Nonetheless, it is preferable to involve the patient, the patient's family, and other specialists on the treatment team in this complex decision, if possible.

REFERENCES

1. Taylor DM, Vater GM, Parker PJ. An evaluation of two tourniquet systems for the control of prehospital lower limb hemorrhage. J Trauma 2011;71(3):591–5.
2. Beekley AC, Sebesta JA, Blackbourne LH, et al. Prehospital tourniquet use in Operation Iraqi Freedom: effect on hemorrhage control and outcomes. J Trauma 2008; 64(Suppl 2):S28–37.
3. Kragh JF Jr, Walters TJ, Baer DG, et al. Practical use of emergency tourniquets to stop bleeding in major limb trauma. J Trauma 2008;64(Suppl 2):S38–49.
4. Kragh JF Jr, Walters TJ, Baer DG, et al. Survival with emergency tourniquet use to stop bleeding in major limb trauma. Ann Surg 2009;249(1):1–7.
5. Kragh JF Jr, O'Neill ML, Walters TJ, et al. Minor morbidity with emergency tourniquet use to stop bleeding in severe limb trauma: research, history, and reconciling advocates and abolitionists. Mil Med 2011;176(7):817–23.
6. Lakstein D, Blumenfeld A, Sokolov T, et al. Tourniquets for hemorrhage control on the battlefield: a 4-year accumulated experience. J Trauma 2003;54(Suppl 5): S221–5.
7. Kragh JF Jr, Baer DG, Walters TJ. Extended (16-hour) tourniquet application after combat wounds: a case report and review of the current literature. J Orthop Trauma 2007;21(4):274–8.
8. Burkhardt GE, Gifford SM, Propper B, et al. The impact of ischemic intervals on neuromuscular recovery in a porcine (Sus scrofa) survival model of extremity vascular injury. J Vasc Surg 2011;53(1):165–73.
9. Hancock HM, Stannard A, Burkhardt GE, et al. Hemorrhagic shock worsens neuromuscular recovery in a porcine model of hind limb vascular injury and ischemia-reperfusion. J Vasc Surg 2011;53(4):1052–62.
10. Kheirabadi B. Evaluation of topical hemostatic agents for combat wound treatment. US Army Med Dep J 2011;25–37.
11. Gordy SD, Rhee P, Schreiber MA. Military applications of novel hemostatic devices. Expert Rev Med Devices 2011;8(1):41–7.
12. Ran Y, Hadad E, Daher S, et al. Quik Clot Combat Gauze use for hemorrhage control in military trauma: January 2009 Israel Defense Force experience in the Gaza Strip—a preliminary report of 14 cases. Prehosp Disaster Med 2010;25(6):584–8.
13. MacIntyre AD, Quick JA, Barnes SL. Hemostatic dressings reduce tourniquet time while maintaining hemorrhage control. Am Surg 2011;77(2):162–5.
14. Bosse MJ, MacKenzie EJ, Kellam JF, et al. A prospective evaluation of the clinical utility of the lower-extremity injury-severity scores. J Bone Joint Surg Am 2001; 83A(1):3–14.
15. Gregory RT, Gould RJ, Peclet M, et al. The mangled extremity syndrome (M.E.S.): a severity grading system for multisystem injury of the extremity. J Trauma 1985; 25(12):1147–50.

16. Howe HR Jr, Poole GV Jr, Hansen KJ, et al. Salvage of lower extremities following combined orthopedic and vascular trauma. A predictive salvage index. Am Surg 1987;53(4):205–8.
17. Johansen K, Daines M, Howey T, et al. Objective criteria accurately predict amputation following lower extremity trauma. J Trauma 1990;30(5):568–72.
18. McNamara MG, Heckman JD, Corley FG. Severe open fractures of the lower extremity: a retrospective evaluation of the Mangled Extremity Severity Score (MESS). J Orthop Trauma 1994;8(2):81–7.
19. Seekamp A, Regel G, Ruffert S, et al. Amputation or reconstruction of IIIB and IIIC open tibial fracture. Decision criteria in the acute phase and late functional outcome. Unfallchirurg 1998;101(5):360–9 [in German].
20. Sudkamp N, Haas N, Flory PJ, et al. Criteria for amputation, reconstruction and replantation of extremities in multiple trauma patients. Chirurg 1989;60(11): 774–81 [in German].
21. Bonanni F, Rhodes M, Lucke JF. The futility of predictive scoring of mangled lower extremities. J Trauma 1993;34(1):99–104.
22. Durham RM, Mistry BM, Mazuski JE, et al. Outcome and utility of scoring systems in the management of the mangled extremity. Am J Surg 1996;172(5):569–73.
23. Hoogendoorn JM, van der Werken CC. The mangled leg. Eur J Trauma 2002; 28:1–10.
24. Bosse MJ, MacKenzie EJ, Kellam JF, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. N Engl J Med 2002;347(24): 1924–31.
25. MacKenzie EJ, Bosse MJ, Kellam JF, et al. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. J Trauma 2002;52(4):641–9.
26. Scalea TM, Dubose J, Moore EE, et al. Western Trauma Association Critical Decisions in Trauma: management of the mangled extremity. J Trauma 2012; 72(1):86–93.
27. Brown KV, Ramasamy A, McLeod J, et al. Predicting the need for early amputation in ballistic mangled extremity injuries. J Trauma 2009;66(Suppl 4):S93–7.
28. Borut LT, Acosta CJ, Tadlock LC, et al. The use of temporary vascular shunts in military extremity wounds: a preliminary outcome analysis with 2-year follow-up. J Trauma 2010;69(1):174–8.
29. Brounts LR, Wickel D, Arrington ED, et al. The use of a temporary intraluminal shunt to restore lower limb perfusion over a 4,000 mile air evacuation in a special operations military setting: a case report. Clinical Medicine Insights: Trauma and Intensive Medicine 2012;1(1):5–9. Available at: http://www.la-press.com/the-use-of-a-temporary-intraluminal-shunt-to-restore-lower-limb-perfus-article-a1007. Accessed March 1, 2012.
30. Taller J, Kamdar JP, Greene JA, et al. Temporary vascular shunts as initial treatment of proximal extremity vascular injuries during combat operations: the new standard of care at Echelon II facilities? J Trauma 2008;65(3):595–603.
31. Chambers LW, Green DJ, Sample K, et al. Tactical surgical intervention with temporary shunting of peripheral vascular trauma sustained during Operation Iraqi Freedom: one unit's experience. J Trauma 2006;61(4):824–30.
32. Rasmussen TE, Clouse WD, Jenkins DH, et al. The use of temporary vascular shunts as a damage control adjunct in the management of wartime vascular injury. J Trauma 2006;61(1):8–12.
33. Mubarak SJ, Owen CA. Double-incision fasciotomy of the leg for decompression in compartment syndromes. J Bone Joint Surg Am 1977;59(2):184–7.

34. Rorabeck CH, Clarke KM. The pathophysiology of the anterior tibial compartment syndrome: an experimental investigation. J Trauma 1978;18(5):299–304.

35. Place RJ, Rush RM Jr, Arrington ED. Forward surgical team (FST) workload in a special operations environment: the 250th FST in Operation ENDURING FREEDOM. Curr Surg 2003;60(4):418–22.

36. Rush RM Jr, Stockmaster NR, Stinger HK, et al. Supporting the Global War on Terror: a tale of two campaigns featuring the 250th Forward Surgical Team (Airborne). Am J Surg 2005;189(5):564–70.

37. Azar F. Traumatic disorders. In: Canale S, Beaty J, editors. Campbell's operative orthopedics. 11th edition. Philadelphia: Mosby Elsevier; 2007. p. 2737–46.

38. Gelberman RH, Garfin SR, Hergenroeder PT, et al. Compartment syndromes of the forearm: diagnosis and treatment. Clin Orthop Relat Res 1981;161:252–61.

39. Tiwari A, Haq AI, Myint F, et al. Acute compartment syndromes. Br J Surg 2002; 89(4):397–412.

40. McQueen MM, Court-Brown CM. Compartment monitoring in tibial fractures. The pressure threshold for decompression. J Bone Joint Surg Br 1996;78(1):99–104.

41. Gentilello LM, Sanzone A, Wang L, et al. Near-infrared spectroscopy versus compartment pressure for the diagnosis of lower extremity compartmental syndrome using electromyography-determined measurements of neuromuscular function. J Trauma 2001;51(1):1–8.

42. Giannotti G, Cohn SM, Brown M, et al. Utility of near-infrared spectroscopy in the diagnosis of lower extremity compartment syndrome. J Trauma 2000;48(3): 396–9.

43. Arbabi S, Brundage SI, Gentilello LM. Near-infrared spectroscopy: a potential method for continuous, transcutaneous monitoring for compartmental syndrome in critically injured patients. J Trauma 1999;47(5):829–33.

44. Cohen MS, Garfin SR, Hargens AR, et al. Acute compartment syndrome. Effect of dermotomy on fascial decompression in the leg. J Bone Joint Surg Br 1991;73(2): 287–90.

45. Pearse MF, Harry L, Nanchahal J. Acute compartment syndrome of the leg. BMJ 2002;325(7364):557–8.

46. Emergency war surgery, 3rd United States Revision. Washington, DC: Borden Institute; 2004.

47. Chan BL, Witt R, Charrow AP, et al. Mirror therapy for phantom limb pain. N Engl J Med 2007;357(21):2206–7.

48. Forsberg JA, Pepek JM, Wagner S, et al. Heterotopic ossification in high-energy wartime extremity injuries: prevalence and risk factors. J Bone Joint Surg Am 2009;91(5):1084–91.

49. Forsberg JA, Potter BK. Heterotopic ossification in wartime wounds. J Surg Orthop Adv 2010;19(1):54–61.

50. Potter BK, Burns TC, Lacap AP, et al. Heterotopic ossification following traumatic and combat-related amputations. Prevalence, risk factors, and preliminary results of excision. J Bone Joint Surg Am 2007;89(3):476–86.

51. Davis TA, O'Brien FP, Anam K, et al. Heterotopic ossification in complex orthopaedic combat wounds: quantification and characterization of osteogenic precursor cell activity in traumatized muscle. J Bone Joint Surg Am 2011; 93(12):1122–31.

52. Potter BK, Forsberg JA, Davis TA, et al. Heterotopic ossification following combat-related trauma. J Bone Joint Surg Am 2010;2(Suppl 92):74–89.

53. Owens JG, Blair JA, Patzkowski JC, et al. Return to running and sports participation after limb salvage. J Trauma 2011;71(Suppl 1):S120–4.

54. Doukas WC, Hayda RA, Frisch HA, et al. Lower limb amputees fare better than limb-salvage patients in military population. AAOS 2012;4(12). Available at: http://www.aaos.org/news/aaosnow/dec10/clinical12.asp. Accessed April 15, 2012.

55. Resnik L, Meucci MR, Lieberman-Klinger S, et al. Advanced upper limb prosthetic devices: implications for upper limb prosthetic rehabilitation. Arch Phys Med Rehabil 2012;93(4):710–7.

56. Thakor NV, Moore DF, Miranda RA, et al. Special issue of DARPA NEST proceedings. IEEE Trans Neural Syst Rehabil Eng 2012;20(2):113–6.

57. Moore DF, Miranda R, Ling GS. DARPA Nest. IEEE Pulse 2012;3(1):14.

58. Jablecki J, Kaczmarzyk L, Kaczmarzyk J, et al. Unilateral arm transplant 28 years after amputation: fourteen-month result. Transplant Proc 2011;43(9):3563–5.

59. Cavadas PC, Landin L, Thione A, et al. The Spanish experience with hand, forearm, and arm transplantation. Hand Clin 2011;27(4):443–53.

60. Cavadas PC, Ibanez J, Thione A, et al. Bilateral trans-humeral arm transplantation: result at 2 years. Am J Transplant 2011;11(5):1085–90.

61. Landin L, Cavadas PC, Nthumba P, et al. Preliminary results of bilateral arm transplantation. Transplantation 2009;88(5):749–51.

62. Fergason J, Keeling JJ, Bluman EM. Recent advances in lower extremity amputations and prosthetics for the combat injured patient. Foot Ankle Clin 2010;15(1):151–74.